

EXPERIMENTAL STUDIES ON SYENITIC ROCKS IN THE YAMATO MOUNTAINS, EAST ANTARCTICA

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Abstract: The stability of amphibole was studied in the presence of syenite composition liquid. The melting relationships of three hornblende clinopyroxene quartz syenites and a hornblende two-pyroxene syenite from the Yamato Mountains were determined in the temperature range of 650–900°C, under a water pressure of 0.05–0.3 GPa and oxygen fugacities of the FMQ buffer. Experimental results of hornblende clinopyroxene quartz syenites (Y406 and Y904) and one hornblende two-pyroxene syenite (Y557) at 0.1 GPa show that melting begins between 720°C and 770°C, and amphiboles disappear between 810°C and 895°C. With the increasing temperature at 0.1 GPa, quartz disappears first, then plagioclase and amphibole in that order. The water saturated solidus temperature of a normative quartz-free hornblende clinopyroxene mela-syenite (Y405) is about 780°C at 0.1 GPa. K-feldspar in this sample disappears at lower temperature than amphibole. In two syenites (Y557 and Y904), solidus and the stability limit line of amphibole intersect at a lower pressure than 0.3 GPa. Moreover, all rocks investigated are at least 40% melted at temperatures ~50°C above the solidus. The present results suggest that amphibole in these syenites could crystallize at pressures lower than 0.3 GPa (~10 km in depth), indicating their emplacements at a relatively shallow crustal level.

1. Introduction

It is difficult to determine the emplacement pressure of plutonic rocks in which no calibrated geobarometer is available for mineral assemblages. We attempt to estimate the pressure of the amphibole-bearing syenites on the basis of the melting experiments. Because the stability limit curve of amphibole changes its *P-T* slope from positive at low pressure to negative at high pressure, and it intersects with a solidus of syenite at two pressure points, the higher and lower limits of the amphibole stability field occur in the supersolidus condition. Syenite would constrain the lowest and highest pressure conditions of their crystallization and emplacement. Amphibole-bearing syenitic rocks from the Yamato Mountains, East Antarctica are chosen for starting material in the melting experiments.

2. Petrography and Petrochemistry of the Syenitic Rocks

The Yamato Mountains (71.5°S , 35.5°E) are made up of late Proterozoic to early Paleozoic high grade regional metamorphic rocks and syenitic and granitic rocks (KIZAKI, 1965 ; SHIRAISHI *et al.*, 1983a). The syenitic rocks occur as isolated masses and nunataks scattered over a distance of 50 km (Fig. 1). The syenitic rocks in the Yamato Mountains have been studied in some detail by SHIRAISHI *et al.* (1983b). They classified the syenitic rocks into three major types in terms of the mode of occurrence and petrography: two pyroxene syenite, clinopyroxene quartz monzo-syenite and clinopyroxene syenite. Among them, the clinopyroxene quartz monzo-syenite is the latest intrusive. Although the intrusive relationships among other earlier syenites and the surrounding metamorphic rocks are not clear due to lack of exposures, the syenites include large blocks of granulites of calcareous and

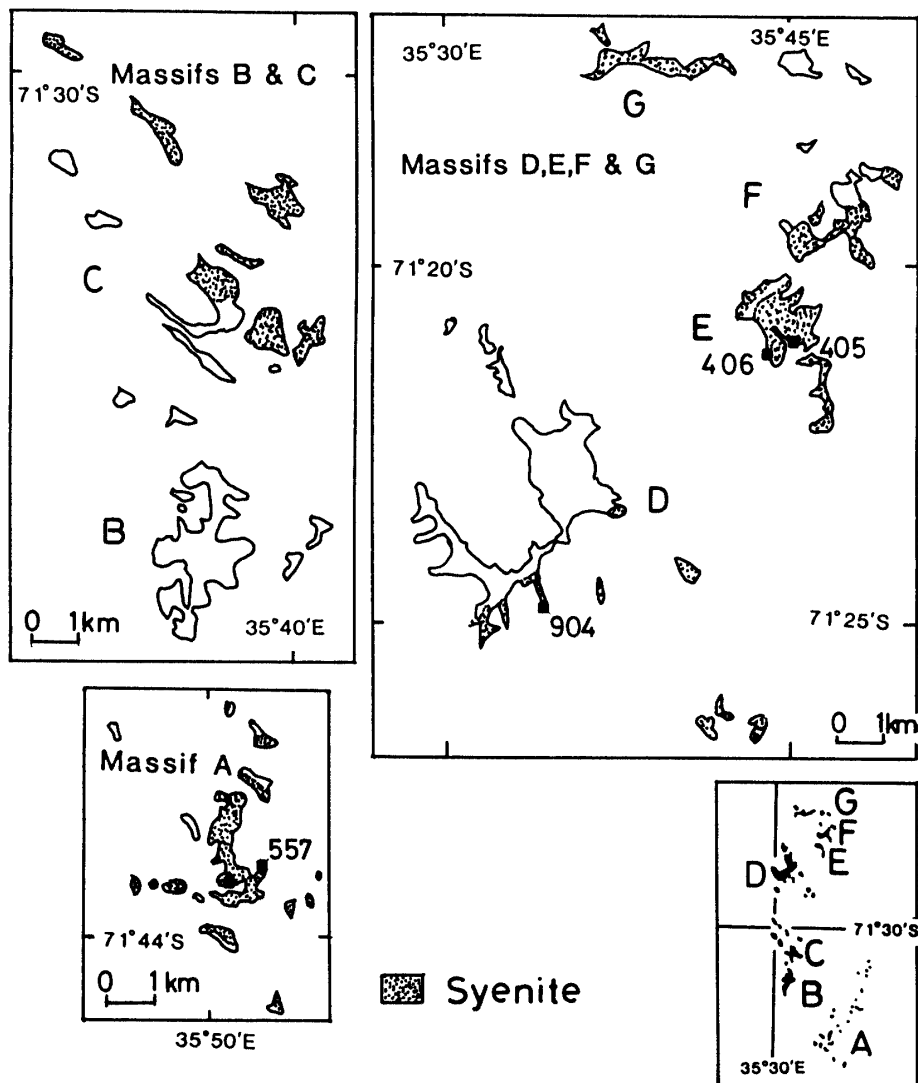


Fig. 1. Map showing the distribution of the syenitic rocks and localities of the samples, modified from SHIRAISHI *et al.* (1983b).

semipelitic compositions in places. Emplacement of the syenite is thought to have taken place during or in the waning stage of the granulite facies metamorphism (SHIRAISHI *et al.*, 1983a).

For the present work, three clinopyroxene syenites are used from the northern Yamato Mountains. In addition, a two-pyroxene syenite from the southern Yamato Mountains was used for comparison (Fig. 1). The clinopyroxene syenite alternates with a mafic-rich melanocratic variety 2–50 m wide in places. According to IUGS nomenclature (STRECKEISEN, 1976), syenites Y405 (73120405) and Y406 (73120406) are classified as fine-grained clinopyroxene hornblende mela-syenite and fine-grained hornblende clinopyroxene quartz syenite, respectively. Syenite Y904 (73120904) is medium-grained hornblende clinopyroxene quartz syenite. Syenite Y557 (Y80A557) is fine grained K-feldspar porphyritic hornblende two-pyroxene quartz syenite.

The syenites are composed of porphyritic K-feldspar, plagioclase, quartz, biotite, Ca-amphibole, clinopyroxene with or without orthopyroxene, sphene and ilmenite. Though the syenites consist of the same mineral assemblages without orthopyroxene, the modal composition and chemical compositions of Ca-amphibole are variable (Fig. 2). Hornblende together with biotite and clinopyroxene shows glomeroporphyritic texture with sharp grain boundaries, suggesting primary igneous

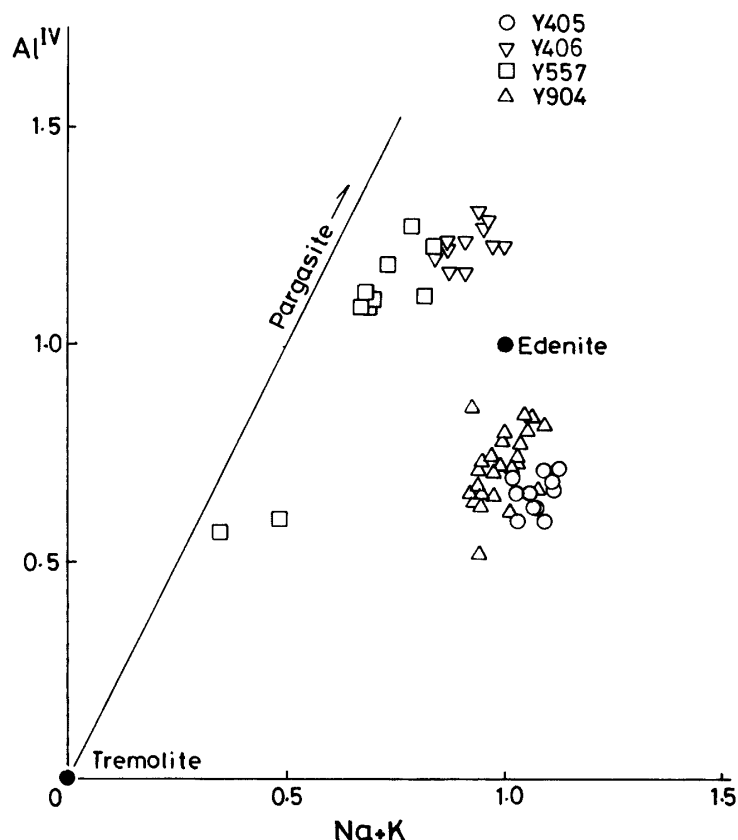


Fig. 2. The chemical variation of Ca-amphiboles in syenites from the Yamato Mountains, expressed as the numbers of (Na+K) vs. Al^{IV} atoms per formula unit.

origin. The marginal parts of clinopyroxene and orthopyroxene in syenite Y557 are partly replaced by green hornblende with actinolitic hornblende at the rim. Ca-amphibole in the syenites Y904 and Y405 is edenitic hornblende with high Na-tremolite content (Fig. 2). In the two syenites Y406 and Y557, Ca-amphiboles are plotted between lines representing tremolite-pargasite and tremolite-edenite. According to the classification by DEER *et al.* (1963), the Ca-amphibole is pargasitic hornblende. The average chemical compositions of amphiboles are shown in Table 1. As compared to others, amphibole of Y405 has high Mg/(Mg+Fe) ratio and high alkali content. Clinopyroxene in all syenites is augite. The felsic constituents are K-feldspar and sodic plagioclase with quartz. K-feldspar shows various shapes of perthitic textures.

The chemical analysis data and CIPW norms of the four syenites are given in

Table 1. Chemical compositions of amphiboles from syenitic rocks of the Yamato Mountains.

Sample	Y405	Y406	Y557 mantle	rim	Y904
N	18	13	8	2	36
SiO ₂	48.96	44.31	44.27	49.63	49.46
TiO ₂	0.96	1.50	1.53	0.45	0.94
Al ₂ O ₃	3.74	7.38	7.17	3.82	4.53
Cr ₂ O ₃	0.12	0.07	0.03	0.02	0.06
FeO*	11.88	19.28	18.54	16.56	12.75
MnO	0.28	0.29	0.32	0.20	0.29
MgO	16.42	9.91	10.12	12.82	15.02
CaO	10.11	10.64	11.21	11.79	10.24
Na ₂ O	3.13	2.35	1.71	1.06	2.84
K ₂ O	0.89	1.18	1.18	0.58	0.97
Total	96.49	96.91	96.08	96.93	97.10
On the basis of 23 oxygens					
Si	7.256	6.813	6.841	7.418	7.290
Al(IV)	0.653	1.187	1.159	0.582	0.710
T	7.909	8.000	8.000	8.000	8.000
Al(VI)	—	0.151	0.147	0.091	0.076
Ti	0.107	0.173	0.178	0.051	0.104
Cr	0.014	0.009	0.004	0.002	0.007
Mg	3.628	2.272	2.331	2.857	3.300
Fe	1.251	2.395	2.340	1.999	1.513
M123	5.000	5.000	5.000	5.000	5.000
Fe	0.221	0.084	0.056	0.071	0.059
Mn	0.035	0.038	0.042	0.025	0.036
Ca	1.605	1.753	1.856	1.888	1.617
Na	0.139	0.125	0.046	0.016	0.288
M4	2.000	2.000	2.000	2.000	2.000
Na	0.760	0.576	0.466	0.291	0.524
K	0.168	0.231	0.233	0.111	0.182
A	0.928	0.807	0.699	0.402	0.706
Mg/(Mg+Fe)	0.71	0.48	0.49	0.58	0.68

Table 2. Analyses and CIPW norms of the syenitic rocks from the Yamato Mountains.

Sample	Y904	Y405	Y406	Y557
SiO ₂	65.31	50.70	61.64	61.30
TiO ₂	0.82	1.68	0.77	1.58
Al ₂ O ₃	15.50	7.68	14.72	14.48
FeO*	3.46	10.25	5.28	5.27
MnO	0.03	0.25	0.03	0.09
MgO	0.94	9.35	1.99	2.63
CaO	1.47	9.36	2.81	3.80
Na ₂ O	4.48	3.19	4.36	3.62
K ₂ O	7.51	3.50	7.04	5.83
P ₂ O ₅	0.21	3.54	0.35	0.82
Total	99.73	99.50	98.99	99.42
CIPW norms				
Q	5.5	—	0.2	6.5
Or	44.5	20.8	42.0	34.7
Ab	38.0	20.1	36.9	30.8
An	tr.	—	—	6.1
Ns	—	1.6	0.1	—
Di Wo	2.5	9.8	4.9	3.1
En	0.8	5.5	1.8	1.5
Fs	1.7	3.9	3.2	1.6
Hy En	1.5	9.7	3.2	5.1
Fs	3.3	6.9	5.4	5.7
Ol Fo	—	5.7	—	—
Fa	—	4.5	—	—
Il	1.6	3.2	1.5	3.0
Ap	0.5	8.2	0.8	1.9
Total	99.9	99.9	100.0	100.0
K ₂ O/Na ₂ O	1.7	1.1	1.6	1.6

* Total Fe expressed as FeO.

Table 2. The trend of syenitic rocks in the AFM diagram is higher in MgO/(FeO + MgO) than that of the intrusive charnockitoids from Central Queen Maud Land, East Antarctica (SHIRAISHI *et al.*, 1983b). The three syenites except for Y405 have similar chemical compositions and normative Qz. The K₂O/Na₂O ratios of all syenites are higher than 1.

3. Experimental Method

The experiments were performed in standard 'cold seal' pressure vessels. Temperatures were measured with chromel-alumel thermocouples. The buffer technique utilized a double capsule system: silver for the outer capsule, and Ag₉₀Pd₁₀ for the inner one (EUGSTER and WONES, 1962). H₂O was always in excess (6–10 wt%). The rock sample for the starting materials was crushed in a stainless mortar, and was ground for 5 hours together with ethyl alcohol in an agate mortar. The grain size of the starting material was 50 μ m maximum (30 μ m on average). Run durations

Table 3. Experimental results for the five syenitic rocks from the Yamato Mountains.

	Temp. (°C)	Press. (GPa)	Time (h)	Results
Y904	680	0.05	336	Amph, Cpx, Bt, K-fld, Qz, Pl
	725	0.05	227	Amph, Cpx, K-fld, Qz, Pl
	750	0.05	160	Amph, Bt, Cpx, K-fld, Qz, Pl
	800	0.05	216	Amph, Cpx, K-fld, Pl, Sph, Gl
	840	0.05	262	Cpx, K-fld, Gl
	880	0.05	141	Cpx, K-fld, Sph, Gl
	725	0.1	160	Amph, Bt, Cpx, K-fld, tr.Qz, Pl
	750	0.1	158	Amph, Bt, Cpx, K-fld, Qz, Pl, tr.Gl
	800	0.1	168	Amph, Bt, Cpx, K-fld, Gl
	820	0.1	338	Cpx, K-fld, Gl
	850	0.1	135	Cpx, K-fld, Gl, (quench Bt)
	900	0.1	118	Cpx, K-fld, Gl
	675	0.15	300	Amph, Bt, K-fld, Qz, Pl
	700	0.15	338	Amph, Bt, tr.Cpx, K-fld, Qz, Pl, tr.Gl
	725	0.15	300	Amph, Bt, Cpx, K-fld, Qz, Pl, Gl
	750	0.15	337	Amph, Bt, Cpx, K-fld, Qz, Pl, Gl
	775	0.15	245	Amph, Bt, Cpx, K-fld, Gl
	800	0.15	143	Amph, Bt, Cpx, K-fld, Gl
	810	0.15	143	Amph, Bt, Cpx, K-fld, Pl, tr.Sph, Gl
	835	0.15	156	Amph, Bt, Cpx, K-fld, tr.Sph, Gl
	865	0.15	156	Bt, Cpx, K-fld, Gl
	740	0.2	304	Amph, Bt, Cpx, K-fld, Pl, tr.Opaq. Gl
	780	0.2	279	Bt, Cpx, K-fld, tr.Opaq. Gl
	685	0.25	310	Amph, Bt, Cpx, K-fld, Qz, Pl
	715	0.25	354	tr.Amph Bt, Cpx, K-fld, Sph, Gl
	740	0.25	312	Bt, Cpx, K-fld, Sph, Gl
	650	0.3	370	Amph, Bt, Cpx, K-fld, Qz, Pl
	675	0.3	412	Bt, Cpx, K-fld, Qz, Pl
	700	0.3	200	Bt, Cpx, K-fld, Pl, tr.Gl
	750	0.3	100	Bt, Cpx, K-fld, Gl
	800	0.3	56	Bt, Cpx, K-fld, Gl
Y405	750	0.1	158	Amph, Bt, K-fld, Qz, Pl
	800	0.1	168	Amph, Cpx, K-fld, Pl, Gl
	675	0.3	412	Amph, Bt, K-fld, Gl
	740	0.3	100	Amph, Bt, Cpx, K-fld, Gl
	880	0.3	99	Amph, Bt, Cpx, Gl
Y406	775	0.05	230	Amph, Bt, Cpx, K-fld, Qz, Pl
	850	0.05	232	Amph, Bt, Cpx, K-fld, Qz, Pl, Gl
	875	0.05	207	Amph, Bt, K-fld, Pl, Gl
	750	0.1	282	Amph, Bt, Cpx, K-fld, Qz, Pl
	775	0.1	618	Amph, Bt, K-fld, Qz, Pl Gl
	860	0.1	282	tr.Amph, Bt, Cpx, K-fld, Gl
	890	0.1	173	Bt, Cpx, K-fld, Gl
	650	0.3	370	Amph, Bt, Cpx, K-fld, Qz, Pl
	675	0.3	412	Amph, Bt, Cpx, K-fld, Pl, Gl
	800	0.3	53	Amph, Bt, Cpx, K-fld, tr.Gl
Y557	750	0.05	360	Amph, Bt, Cpx, Opx, K-fld, Qz, Pl
	725	0.1	333	tr.Amph, Bt, Cpx, Opx, K-fld, Qz, Pl
	750	0.1	203	Amph, Bt, Cpx, Opx, K-fld, Qz, Pl, tr.Gl
	800	0.125	252	Amph, Bt, K-fld, Pl, Qz, Gl
	825	0.125	358	tr.Amph, Bt, Cpx, Opx, K-fld, Pl, Gl
	800	0.175	159	tr.Amph, Bt, Cpx, Opx, K-fld, Pl, Gl
	825	0.175	206	Bt, Opx, Opx, K-fld, Pl, Gl
	700	0.2	472	tr.Amph, Bt, Cpx, Opx, K-fld, Qz, Pl
	750	0.2	472	Amph, Bt, Cpx, Opx, K-fld, Qz, Pl, Gl
	800	0.2	186	Bt, tr.Cpx, K-fld, Pl, Gl
	700	0.25	234	Bt, Cpx, Opx, K-fld, Qz, Pl

Amph: amphibole, Bt: biotite, Cpx: clinopyroxene, Opx: orthopyroxene, K-fld: K-feldspar, Qz: quartz, Pl: plagioclase, Sph: sphene, Opaq: opaque mineral, Gl: glass, tr.: trace.

ranged from 53 hours at 800°C and 0.3 GPa to 370 hours under the lower temperature conditions.

The phases were identified with X-ray powder diffraction patterns and a optical microscope. Since optical identification between fine grained K-feldspar and quartz is difficult, it is probable that the disappearance curve of quartz was determined at the slightly lower temperature side of the true disappearance curve.

Major elements of four samples were analyzed by X-ray fluorescence spectrometer (Rigaku S3030 model) at Joetsu University of Education. Chemical compositions of amphibole were determined with a JEOL 733 Superprobe, using standard procedure at the National Institute of Polar Research.

4. Experimental Results

The experimental results are shown in Table 3 and illustrated in Figs. 3 through 6. The water saturated solidus temperatures of Y405 are 780°C at 0.1 GPa and 660°C at 0.3 GPa (Fig. 3). *P-T* curves for the disappearance of quartz and plagioclase are a few degrees above subparallel to the solidus. The curve for the disappearance of K-feldspar is about 100°C above the solidus; both curves are nearly parallel. Amphibole was stable under all water vapor pressures during the present experiment.

The solidus curve of Y406 is 780°C at 0.1 GPa and 660°C at 0.3 GPa (Fig. 4). The curve for the disappearance of quartz is a few tens of degrees above the solidus. Plagioclase (albite) disappears at a higher temperature than quartz. The boundary

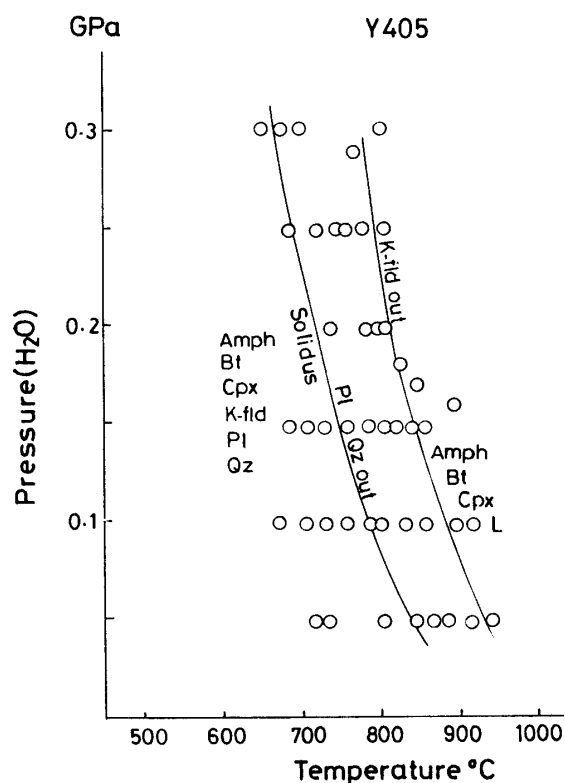


Fig. 3. Phase diagram of the Y405.

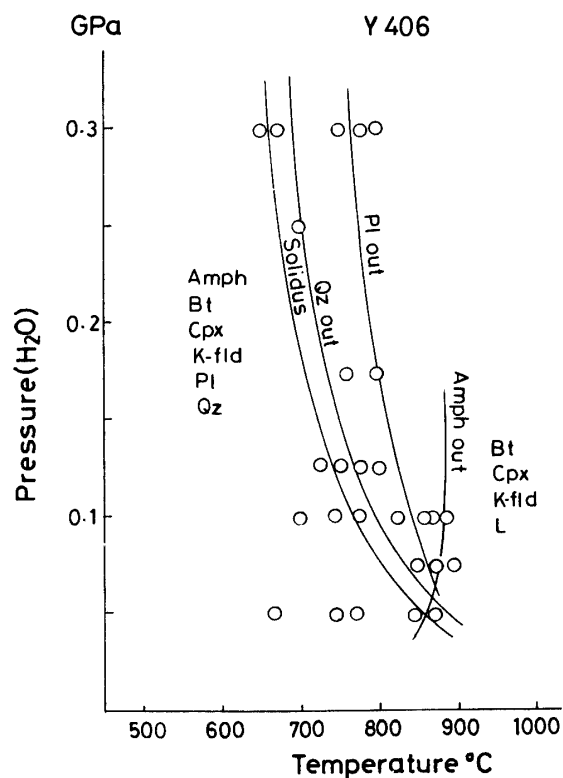


Fig. 4. Phase diagram of the Y406.

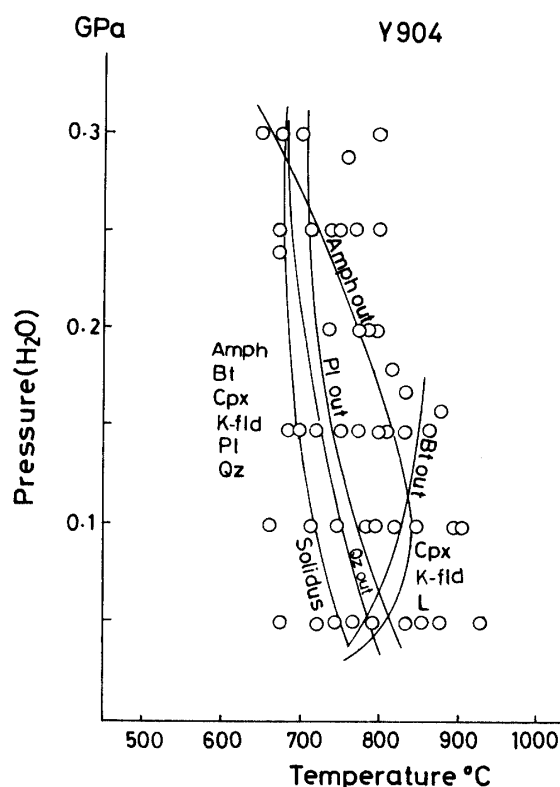


Fig. 5. Phase diagram of the Y904.

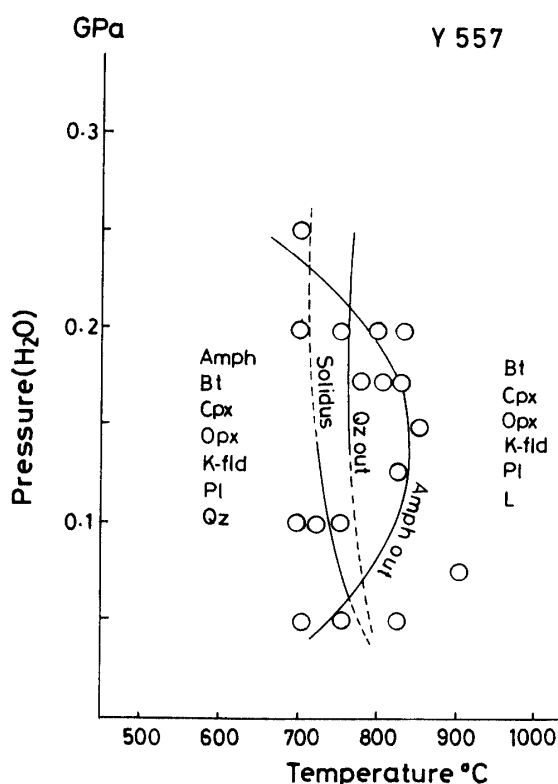


Fig. 6. Phase diagram of the Y557.

for the upper stability limit of amphibole is about 890°C at 0.1 GPa.

Y904 begins to melt at 720°C and 0.1 GPa, and at 700°C and 0.3 GPa, quartz and then plagioclase disappear at about 780°C, amphibole disappears at 850°C (Fig. 5). At the high temperature side of the stability limit of amphibole, clinopyroxene and K-feldspar are still stable. The boundary for the upper stability limit of amphibole intersects with the solidus at 700°C and about 0.28 GPa.

Y557 begins to melt at 730°C and 0.1 GPa (Fig. 6). The stability field of amphibole is very narrow. The high temperature stability limit of amphibole intersects with the solidus at 710°C and about 0.23 GPa.

The supersolids in the melting experiment, except for syenite Y405, disappear with the increasing temperature at 0.1 GPa in the following order: quartz, plagioclase and amphibole.

In Y557 and Y904, the upper pressure stability limit of amphibole intersect the solidi at lower pressure than 0.3 GPa.

5. Discussion

The early experimental studies of granitic rocks were done by Wyllie and co-workers (PIWINSKII, 1968; PIWINSKII and WYLLIE, 1968, 1970; GIBBON and WYLLIE, 1969; ROBERTSON and WYLLIE, 1971). The melting behavior of syenite was studied by McDOWELL and WYLLIE (1971). Little experimental work has been done on the syenite system. However, these experiments under relatively high temperature

condition could not determine the stability field of amphibole. They also could not determine the high pressure stability limit of amphibole by experiment up to 0.3 GPa. Recently, experiments in granitic system were done with under water activities controlled by $\text{CO}_2\text{-H}_2\text{O}$ vapor phase and water content (CLEMENS and WALL, 1981; NANEY, 1983). CLEMENS and WALL (1981) used S-type granite, which is characterized by absence of amphiboles, as the starting material. NANEY (1983) reported that the presence of hornblende in a model granodiorite system may be useful indicator of the minimum H_2O content in the parent magma system. The pressure stability limit of amphibole near the solidus cannot be decided in his experiment between 0.2 GPa and 0.8 GPa.

In the granite system, many experiments have suggested that amphibole has a wide stability field. Granitic rock is not good for starting material.

We could not determine the exact oxygen fugacity of syenitic rocks, because ilmenite did not coexist with magnetite in three syenite and one mela-syenite used for the present experiment. SHIRAISHI *et al.* (1983b) found that ilmenite and magnetite are common opaque minerals in clinopyroxene syenite near three syenitic rocks in the northern part of massifs. The upper stability limits of ferropargasite and hastingsite under FMQ buffer are at higher temperature than those under NNO(Ni-NiO) and MH (magnetite-hematite) buffers (GILBERT, 1966; THOMAS, 1982). SPEAR (1981) reported that the upper thermal stability limits of amphibole are 902°C, 912°C and 908°C, 1 kb on the HM, QFM and WM buffers in olivine tholeiite, respectively. Thus, at low pressure the stability field of amphibole under FMQ buffer is wider than that under NNO buffer, or is similar to that under other buffers. Therefore, the experiment was carried out under FMQ oxygen fugacity.

We consider the shift of the intersection point of the solidus and the amphibole stability limit by the effect of CO_2 fluid. HOLLOWAY (1973) reported that the stability temperature of pargasite below 0.4 GPa decreases with decreasing $X_{\text{H}_2\text{O}}$ at constant pressure. WYLLIE (1977) found that the temperature gap between the H_2O -saturated solidus and undersaturated solidus is less than 0.2 GPa, on the order of 25°C. Therefore, the present experiment under the water-saturated condition and FMQ buffer suggests that amphibole at the low pressure condition has a stability similar field to that under the water-undersaturated condition and FMQ-NNO buffer.

The present results suggest that the intersection of the high pressure stability limit of amphibole and the solidus may indicate the maximum pressure of amphibole crystallization. If amphibole crystallizes in syenitic liquid, the cooling path passes through the stability field of amphibole above the solidus. We suggest that amphibole could have crystallized at pressures less than 0.3 GPa (depth ~ 10 km), probably in a shallow crustal magma chamber. Moreover, all rocks investigated are at least 40% melted at temperatures $\sim 50^\circ\text{C}$ above the solidus, suggesting that the intrusive bodies might be mobile until close to the solidus temperatures.

ASAMI and SHIRAISHI (1985) reported that the peak granulite facies metamorphism at Massif A in the southern Yamato Mountains took place at about 750°C and below 0.6 GPa. This is consistent with the present conclusion that the pressure of the syenite emplacement after the metamorphism should be below 0.6 GPa. Thus,

the regional metamorphism and the subsequent syenite emplacement occurred at the relatively shallow crustal level in the Yamato Mountains.

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